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Sulphide Saturation Mechanisms in Gabbroic Intrusions in the Nipigon Embayment: Lake Nipigon Region Geoscience Initiative

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by

S.A. Kissin, G.J. Heggie and A.K. Somarin

2006

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Abstract

The Seagull and Kitto intrusions in the Nipigon Embayment of northwestern Ontario were studied in order to gain an understanding of the processes involved in sulphur saturation of the mafic to ultramafic magmas leading to the formation of platinum group elements (PGE) concentrations. Profiles of sulphur, copper, nickel, gold, palladium and platinum concentrations as a function of depth revealed that sulphur saturation occurred at the base of the Seagull intrusion. A higher grade horizon occurs well above the base of the intrusion, suggesting that a reef-type of process was significant here and possibly in the Kitto intrusion, as well. Olivine compositions indicate that, in both cases, the parental magmas were undersaturated with respect to sulphur. Sulphur and neodymium–samarium isotopic data suggest that assimilation of country rock and sulphide played a role especially in the formation of basal concentrations of PGEs.

Sulphide Saturation Mechanisms in Gabbroic Intrusions in the Nipigon Embayment: Lake Nipigon Region Geoscience Initiative

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Introduction

The rise in prices of platinum group elements (PGE) at the beginning of the new Millennium has stimulated exploration activity in northwestern Ontario. This activity has been focussed in several areas, but particular interest has centred on the Nipigon Embayment in the wake of the suggestion by Naldrett (1992) that the area is a likely geological setting for the development of nickel-copper-platinum group element (Ni-Cu-PGE) deposits based on criteria established in studies of the Noril'sk deposit in Siberia.

Several PGE occurrences in Proterozoic mafic intrusions have been noted; however, of greatest interest are those in the Seagull intrusion, south of Lake Nipigon, and the Kitto intrusion (formerly named the Eva–Kitto intrusion) on the eastern shore of Lake Nipigon (Figure 1). These two intrusions are hosts to potential ore-grade intersections in drill core (East West Resource Corporation 2004). Hence, they were selected for study, as they are best suited for tests of ore deposit modelling.

The Seagull intrusion is located approximately 90 km north-northeast of Thunder Bay. It is expressed topographically in Wolf Mountain. The prospects on Wolf Mountain are currently in an advanced exploration phase through an option agreement with Platinum Group Metals Ltd. from joint venture partners, East West Resource Corporation and Canadian Golden Dragon Resources Ltd. The property is known as the Wolf Mountain Joint Venture. A history of development activities was given by Heggie (2005).

Drilling activities through 2002 and a summary of the geology are given in Figure 2. The basement rocks of the intrusion are pelitic metasedimentary rocks of the Quetico Subprovince. These rocks contain sparse sulphide mineralization.

The Seagull intrusion, according to Heggie (2005), consists of approximately 100 m of olivine hornblende gabbro, overlain by approximately 400 m of peridotite. Above this is a zone, approximately 300 m thick, consisting of serpentinized peridotite, which contains laterally discontinuous zones of websterite to olivine websterite and plagioclase-bearing pyroxenite. Distal margins of the intrusion contain interlayered plagioclase-bearing pyroxenite and gabbro to hornblende gabbro. Within 100 m of the surface, the serpentinized peridotite is intruded by a Nipigon diabase sill.

The Kitto intrusion is located approximately 135 km northeast of Thunder Bay on the eastern shore of Lake Nipigon. The intrusion is exposed only along its margins and has been explored by only limited drilling. Although detailed work on petrography is currently underway, olivine-rich ultramafic rocks similar to those in the Seagull Intrusion are predominant. Potential ore-grade intersections of PGEs, copper and nickel have been reported (East West Resource Corporation 2004). The property is presently under further exploration by a joint venture between East West Resource Corporation and Maple Minerals Corporation.

THE NORIL'SK MODEL

Interest in the Nipigon Embayment as a promising area for the occurrence of Ni-Cu-PGE ores was stimulated by the work of Naldrett et al. (1992) and Naldrett (1992), who derived a model for the major ore deposits at Noril'sk in northern Siberia. The model is constructed based on the presence of seven geological factors in a given locale: 1) mantle heating giving rise to voluminous basaltic magmatism, 2) continental rifting, 3) fault control of extrusive and intrusive igneous activity, 4) contamination of magma by crustal material, 5) depletion of chalcophile elements in contaminated magma, 6) intrusion of magma with chalcophile elements concentrated from the contaminated magma, and 7) presence of evaporates in sedimentary rocks underlying the basalts.

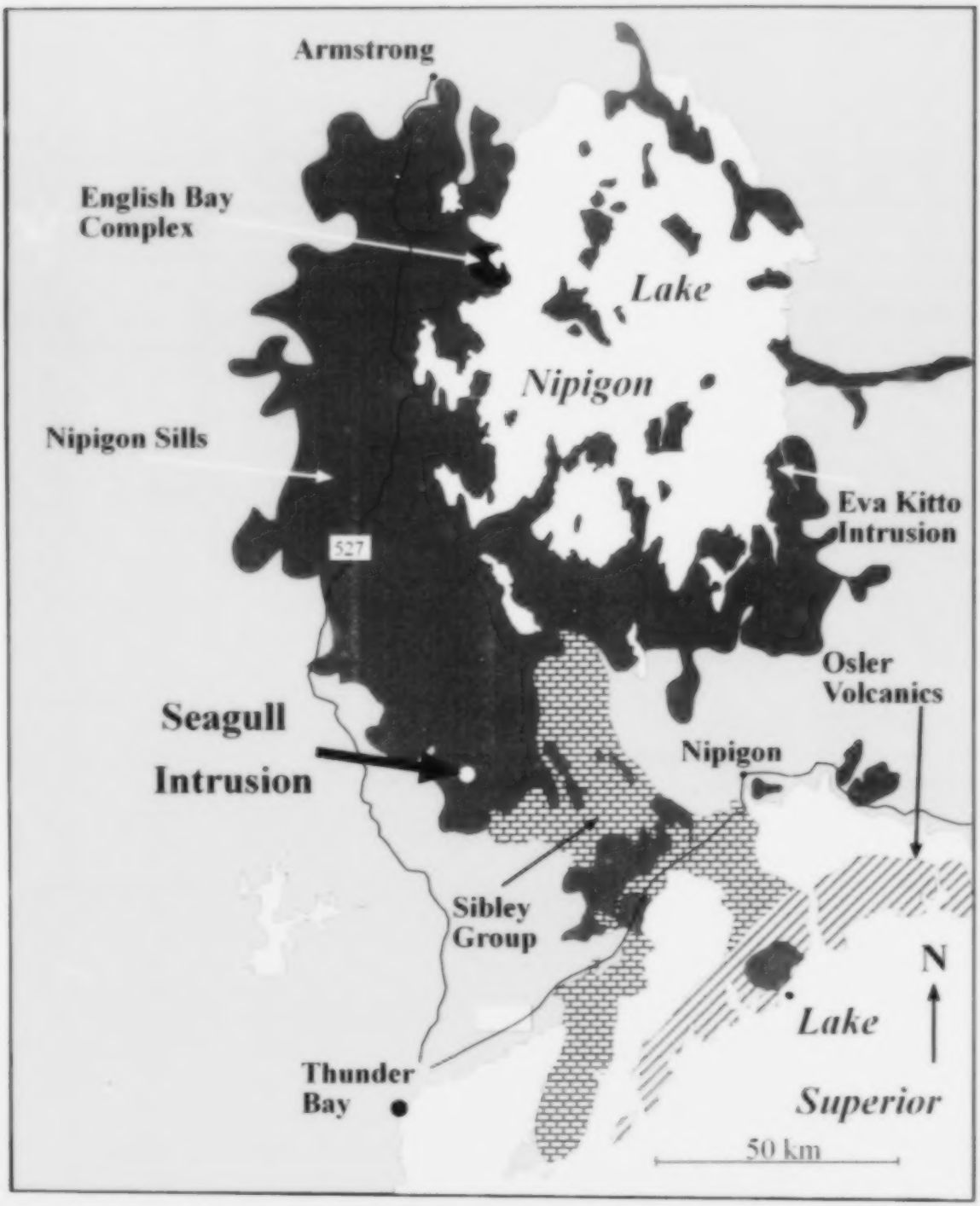

Figure 1. Generalized geological map of the Nipigon Embayment showing the Proterozoic units and locations of the Seagull intrusion and Kitto intrusion.

Naldrett (1992) proposed that the Nipigon Embayment represent a locale wherein all 7 factors favourable for the development of Noril'sk model deposits are present. The appropriateness of the Noril'sk model is examined in the light of this study and other recent work in the Nipigon Embayment.

OTHER MODELS FOR PLATINUM GROUP ELEMENT CONCENTRATION

The "Reef" Model

Naldrett (1993) proposed several subtypes of model processes for formation of stratabound PGE deposits in layered mafic intrusions. Although it is clear that the Seagull and Kitto intrusions are not layered mafic intrusions in the style of the Bushveldt and Stillwater complexes, some of the various processes proposed by Naldrett may apply, especially in the Seagull intrusion.

Experimental and theoretical studies on the behaviour of PGEs in mafic magmas have demonstrated that PGEs as well as chalcophile elements are strongly partitioned into a co-existing, immiscible sulphide melt. The foregoing studies, as well as field-based observations on layered mafic intrusions, indicate that following factors lead to the formation of PGE-rich horizons (Naldrett 1993):

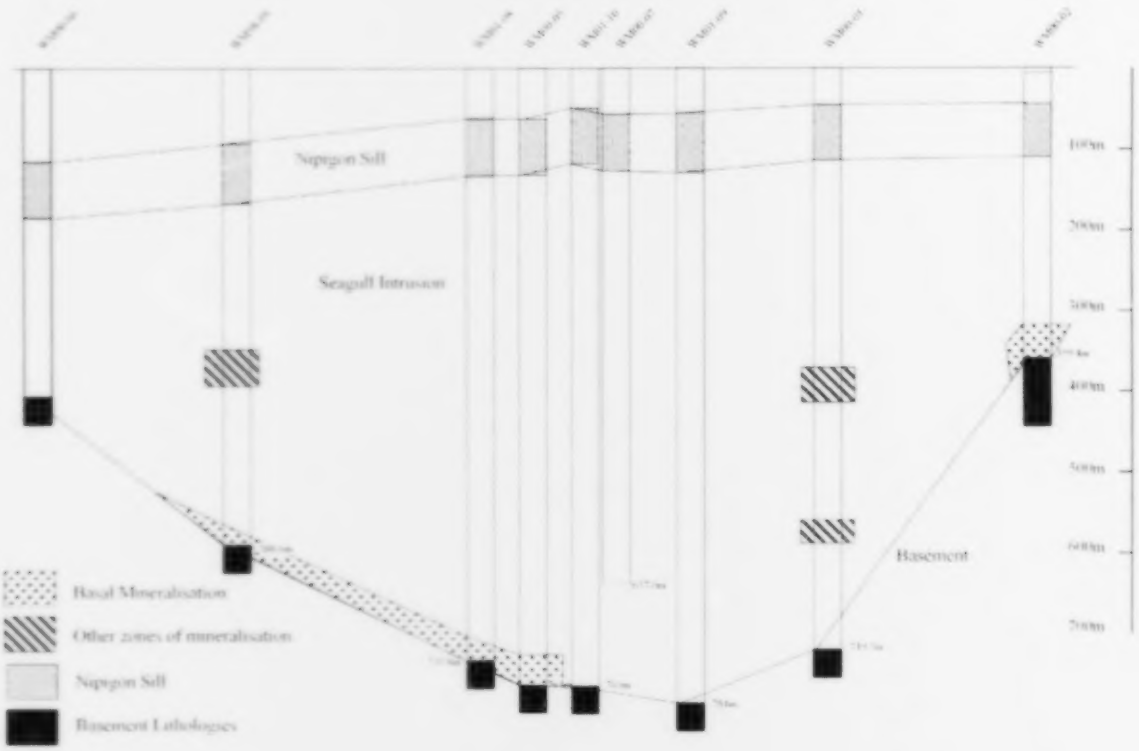

Figure 2. Schematic section of the Seagull intrusion showing the locations of diamond-drill holes and generalized geology (*from* Heggie 2005).

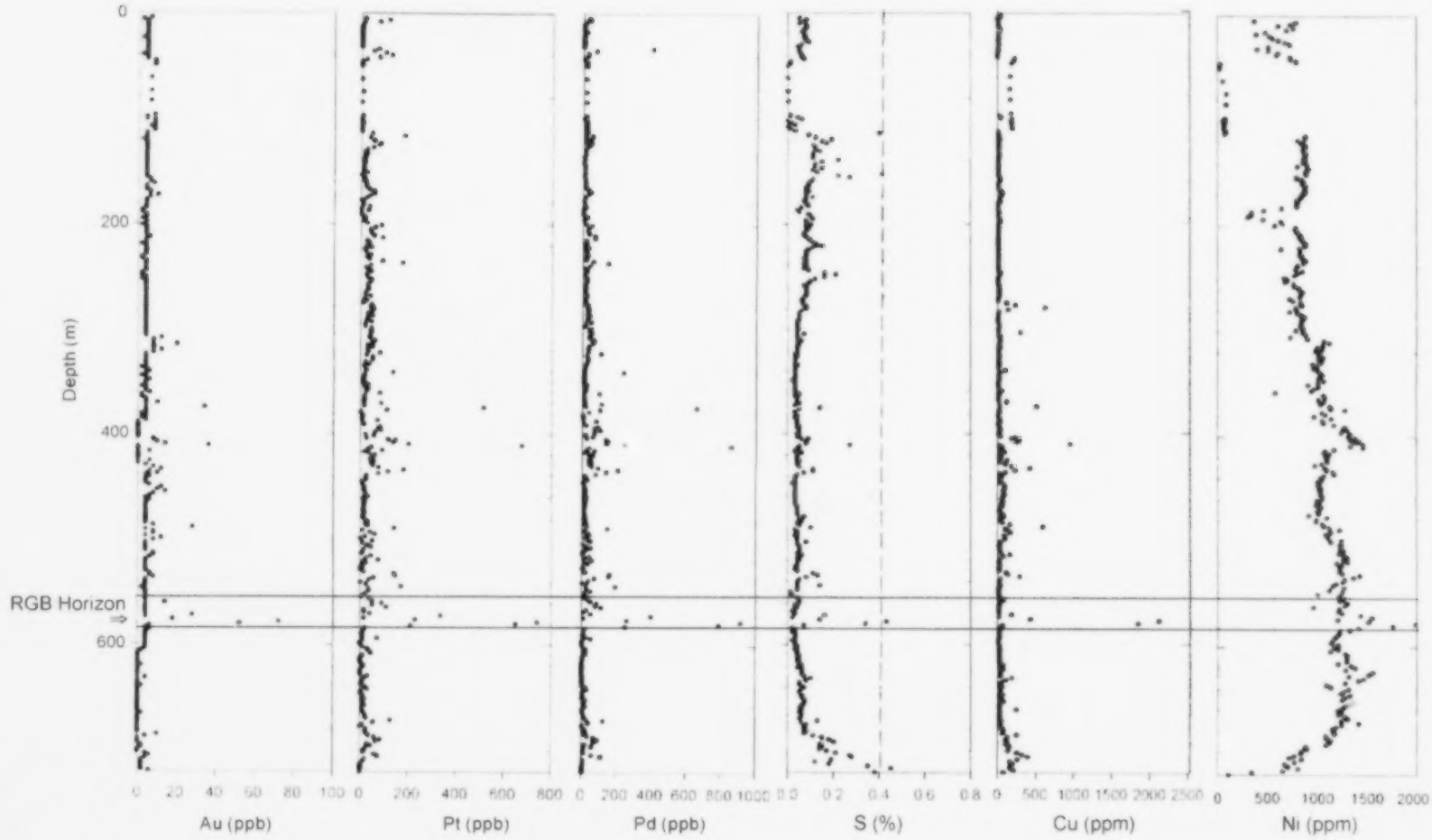

Figure 3. Variation in gold (Au), platinum (Pt), palladium (Pd), sulphur (S), copper (Cu) and nickel (Ni) content with depth in diamond-drill hole WM00-01. The dashed line in the S versus depth plot denotes sulphur saturation at 400 ppm. The location of the RGB Horizon is indicated.

1. the parental magma must be initially undersaturated with respect to sulphur
2. the parental magma must be enriched in PGEs, or PGE enrichment must have been developed during fractional crystallization of the magma.
3. initial production of an immiscible sulphide melt must be the result of a process that produces a high silicate–sulphide melt ratio

Although Naldrett (1993) employed the term "reef" in a more restrictive sense, it is used here more generally for any stratabound concentration of PGEs, as employed by Eckstrand (2005).

Sulphur Saturation in Magmas and Platinum Group Element Concentration

Economic PGE deposits are almost universally associated with mafic or ultramafic igneous rocks (Naldrett 1989). The concentration of PGEs in a sulphide melt separated from a silicate magma is a function of several factors including initial PGE content of the magma, the ratio of the mass of silicate melt to sulphide melt and the distribution coefficient of the particular PGE. The latter is known to be very large (on the order of 10^5) for mafic and ultramafic melts (Naldrett 1989). Thus, in a sulphur-undersaturated melt, separation of a sulphide melt will strongly concentrate PGEs from the silicate magma.

PLATINUM GROUP ELEMENT AND CHALCOPHILE ELEMENT CONCENTRATIONS

According to Boudreau and McCallum (1992), a gabbro cumulate crystallized from a sulphur-saturated magma should contain more than 400 ppm sulphur. Following a methodology employed by Miller (1999), analyses of rock for copper (Cu) and nickel (Ni), which also partition strongly to the sulphide melt, as well as for sulphur (S), gold (Au), palladium (Pd) and platinum (Pt) will indicate the position of PGE concentration in a mafic to ultramafic intrusion.

The approach was employed in diamond-drill hole WM00-01 analytical data obtained from the Wolf Mountain Joint Venture. The diamond-drill hole completely penetrated the Seagull intrusion to a depth of 720 m and passed into Quetico Subprovince metasedimentary rocks to a total depth of 820 m. A detailed petrographic description of the rock types encountered is given by Heggie and Hollings (2003).

Figure 3 illustrates the variation in S content and corresponding variations in Cu, Ni, Au, Pd and Pt with depth in WM00-01. In Figure 3, the line at 0.4% S (400 ppm) indicates the theoretical threshold for sulphur saturation of the magma. Examination of this plot reveals that sulphur saturation occurred for an interval of about 10 m at the base of the Seagull intrusion and for a similar interval near 580 m, as well as 2 additional intervals at approximately 140 m and 120 m. A spike in sulphur content at 420 m is below the 400 ppm threshold, but appears, nevertheless, to be significant.

At both the 580 m and 420 m levels, there are marked increases in both Cu and Ni contents, corresponding to fractionation of these metals into the sulphide melt. However, the significant sulphur saturation at the base of the intrusion is not accompanied by increases in Cu and Ni content. In fact, the Ni content is anomalously lower than in overlying rocks. Moreover, Au, Pd and Pt contents are only slightly elevated.

Table 1. Nickel contents and forsterite proportion (fo) of olivines from diamond-drill hole WM00-01.

Sample Number	Depth (m)	Forsterite (fo)	Ni (ppm)	NiO (wt %)
SW01-19	332.39	82.5	1635	0.2081
SW01-22	376.92	83.3	2029	0.2583
SW01-25	477.70	82.6	1498	0.1907
SW01-29	573.40	83.8	2077	0.2644
SW01-32	583.70	83.3	1975	0.2514
SW01-35	647.00	81.7	1927	0.2453

Table 2. Olivine composition from the Kitto intrusion.

Sample Number	02-303.23	02-303-23B	02-303-23C	02-303-23D	02-303-23E
MgO (wt %)	38.34	38.34	38.28	37.61	38.57
SiO_2	37.80	37.80	37.86	37.90	37.96
CaO	0.05	0.05	0.03	0.04	0.03
MnO	0.28	0.28	0.30	0.32	0.27
FeO	23.48	23.48	23.34	24.44	23.27
NiO	0 20	0.20	0.17	0.18	0.18
Total	100.15	100.15	99.98	100.49	100.28
fo	74.6	74.6	74.5	73.13	74.63
Ni (ppm)	1500.00	1491.20	1267.52	1342.08	1342.08
Mg (cations)	1.50	1.50	1.49	1.47	1.50
Si	0.99	0.99	0.99	0.99	0.99
Ca	0.00	0.00	0.00	0.00	0.00
Mn	0.01	0.01	0.01	0.01	0.01
Fe	0.51	0.51	0.51	0.54	0.51
Ni	0.00	0.00	0.00	0.00	0.00
Total	3.01	3.01	3.00	3.01	3.01

On the other hand, at 420 m and especially 580 m, marked spikes in Au, Pd and Pt are present. The latter is now recognized as a significant zone of mineralization, designated as the RGB Horizon. Plots of element distribution in other Wolf Mountain diamond-drill holes are shown as Figures 4 to 8 in Appendix 1.

OLIVINE COMPOSITIONS AS A FUNCTION OF SULPHIDE SATURATION

Duke and Naldrett (1978) demonstrated that the composition of olivine, in terms of proportion of forsterite (fo) and NiO content, varies with the sulphur content of mafic magmas. Compositions from WM00-01 determined by electron microprobe from various depths in the intrusion are given in Table 1. Considerably more olivine compositions were determined by Heggie (2005); however, NiO contents were at or below detection limits. Table 2 provides compositional data on olivines from the Kitto intrusion as determined in this study. Due to the scarcity of olivine in most samples, sampling from only one depth in the intrusion was possible.

The ranges of olivine compositions are plotted in Figure 4 in which a generalized saturation curve taken from Cawthorne and Kruger (2004) separates the field of sulphur-saturated magma from the field of unsaturated magma. It is significant both that the ranges of olivine compositions are small in both intrusions and that both are undersaturated with respect to sulphur.

Magmatic Contamination as a Sulphide Precipitation Mechanism

The significance of contamination of mafic magma, either through assimilation of country rock or magma mixing, has for some time been ascribed a crucial role in the formation of an immiscible sulphide melt (Irvine 1975; Naldrett 1989). A test for contamination can be made through the study of neodymium (Nd)–samarium (Sm) isotopes. Heggie (2005) reported complete data on Nd/Sm isotopic studies on samples from the Seagull intrusion at a range of depths. These were compared limited data from the Quetico Subprovince and Sibley Group sedimentary rocks.

The samples from the Seagull intrusion yielded ε_{Nd} ranging from –0.2 to –4.0 (±0.5). Both the Quetico Subprovince and Sibley Group data yielded negative ε_{Nd} values with a range of –16 to –23 for Quetico Subprovince samples and a mean of –5 for Sibley Group samples.

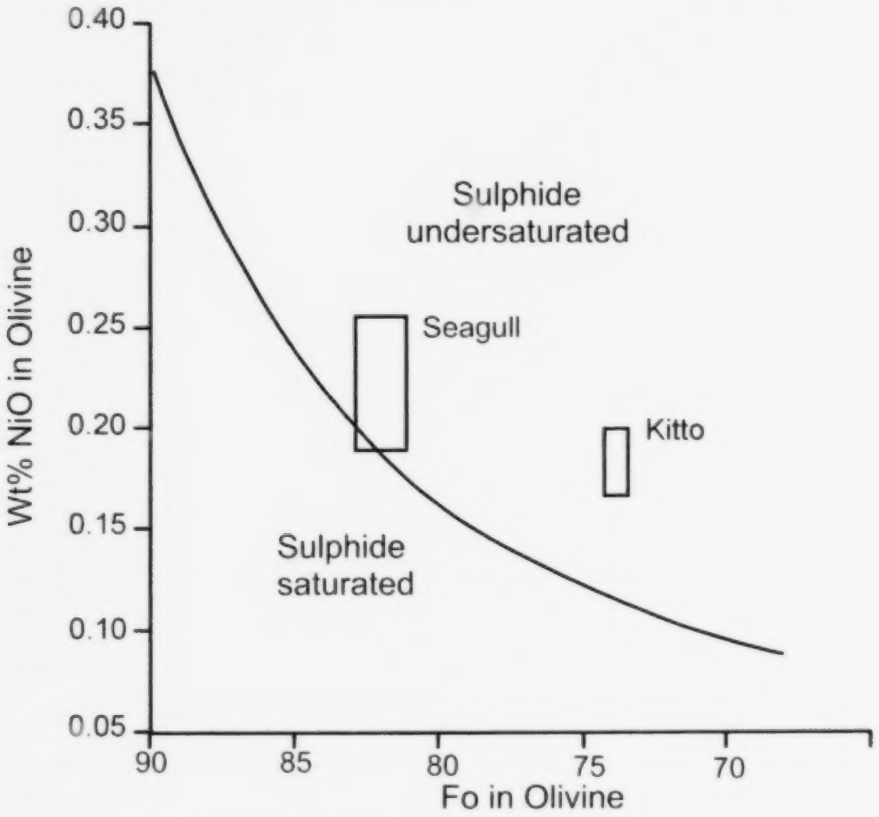

Figure 4. NiO versus forsterite content (fo) in olivine from the Seagull and Kitto intrusions. The sulphide saturation curve is *from* Cawthorne and Kruger (2004) *after* Duke and Naldrett (1979).

Comparison of $^{143}Nd/^{144}Nd$ versus $^{87}Sr/^{86}Sr$ by Heggie (2005) revealed that Sibley Group samples differ markedly in $^{87}Sr/^{86}Sr$, whereas the Quetico Subprovince samples all lie within the range of values obtained for the Seagull intrusion samples. As the ε_{Nd} for the Seagull intrusion samples depart from the mantle value of $\varepsilon_{Nd} = 0$ and are increasingly negative toward the base of the intrusion, assimilation of Quetico Subprovince metapelites seems a plausible source of contamination.

Source of Sulphur in Sulphides

Attempts were made in the present study to obtain sufficient sample material for sulphur isotopic analyses. However, examination of all available diamond-drill core revealed that samples in which more than the minimum 100 mg necessary for analyses were removed either for the commercial purposes of the developer or for prior sulphur isotopic analyses by J.M. Franklin (Franklin Geosciences Ltd., personal communication, 2001).

Franklin reported data for several Wolf Mountain Joint Venture diamond-drill holes including sulphide-bearing metapelites from the base of the intrusion and evaporites from the Sibley Group sedimentary rocks, which overlie the Quetico Subprovince metasedimentary rocks. Sulphides from the Seagull intrusion had $\delta^{34}S$ ranging from –2.3 per mil (‰) to +2.6‰ with a mean value of –0.9‰. Sulphides in Quetico Subprovince metapelites has $\delta^{34}S$ ranging from –2.3‰ to +1.1‰ with a mean value –0.8‰. Finally, Sibley Group evaporites had $\delta^{34}S$ ranging from +7.7‰ to +9.0‰. According to Franklin, these correspond to a mean H_2S composition of –4.2‰, based on prior knowledge of temperatures of formation of the sulphate minerals (barite, anhydrite and gypsum) in the Sibley Group.

The similarity between the sulphur isotopic data between samples from the Quetico Subprovince metapelites and the Seagull intrusion provides plausible evidence for incorporation of Quetico Subprovince sulphides by the intrusion. This is especially true for the sulphide-bearing zone at the base of the intrusion. On the other hand, the isotopic composition is very close to the theoretical mantle sulphide composition of $\delta^{34}S = 0$‰. Sibley Group evaporite sulphate does not seem to be a viable source for sulphur in the Seagull intrusion.

Discussion

As indicated earlier, the Noril'sk model has been foremost in the minds of those pursuing PGE deposits in the Nipigon Embayment. The prerequisites for the application of the Noril'sk model according to Naldrett (1992), as stated previously, do not seem to all have been fulfilled in the case of the Seagull intrusion; however, owing to as yet incomplete data on the Kitto intrusion, the model may apply there. The tectonic setting of mantle heating and continental rifting are clearly present in the Nipigon Embayment. As well, the voluminous basaltic magma, with crustal contamination, is also present in the form of the Osler Volcanic Group, which is related to the North Shore Volcanic Group. Sulphate-bearing evaporates are also present in the Sibley Group, which underlies the Osler Volcanic Group.

The major problem is the timing of igneous events in the Nipigon Embayment. The Seagull intrusion, although has not had a direct age determination, is cut by a Nipigon diabase sill. The Nipigon sills have an age of $1108\ ^{+4}/_{-2}$ Ma, as determined by Davis and Sutcliffe (1985). Thus, the Seagull intrusion and possibly other mafic to ultramafic intrusions are apparently the earliest igneous activity associated with the Midcontinent Rift.

The extensive volcanism of the Midcontinent Rift commenced at 1108±1 Ma, but the majority of activity occurred in the period 1100 to 1094 Ma after a quiescent period of 8 Ma (Davis and Green 1997). Thus, the relative timing of intrusive and extrusive is the reverse of that required in the Noril'sk model. The evaporates in the Sibley Group, moreover, do not appear to be a plausible source of sulphur for sulphides.

Although the Noril'sk model does not appear to be tenable in the case of the Seagull intrusion, the possibility of both assimilation of sulphide and contamination by country rock seems to offer an explanation for the sulphide horizon at the base of the Seagull intrusion. The somewhat lower tenor of PGEs and chalcophile elements here, as opposed to those in the horizons higher in the intrusion may be the result of more rapid cooling at the base. Thus, the silicate magma may not have reached equilibrium with sulphide melt.

The RGB Horizon and other zones higher in the intrusion appear to have formed by processes more akin to a reef-type model. The prerequisites of the model seem to have been fulfilled in that the parental magma was clearly undersaturated with respect to sulphur, as seen in the olivine data. The low concentration of sulphides in those horizons is indicative of a high ratio of silicate melt to sulphide melt. Although the relative PGE content of the parental magma cannot be assessed, it is evidently sufficient to have been the source of significant PGEs in both the Seagull and Kitto intrusions.

Conclusions

The aspects of the Seagull and Kitto intrusions, as related to the PGE occurrences they contain, are suggestive of formation of reef-type deposits, especially in the Seagull intrusion. The Noril'sk model does not appear applicable in these cases owing to difficulties in the relative timing of igneous events required in the model. Some basal sulphide and PGE concentrations may be attributable to assimilation of sulphide and contamination by country rock.

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Appendix 1

Plots of Variations of Gold, Platinum, Palladium, Sulphur, Copper and Nickel Content with Depth in Core from Selected Seagull Intrusion (WM) and Kitto Intrusion (EK) Diamond-Drill Core

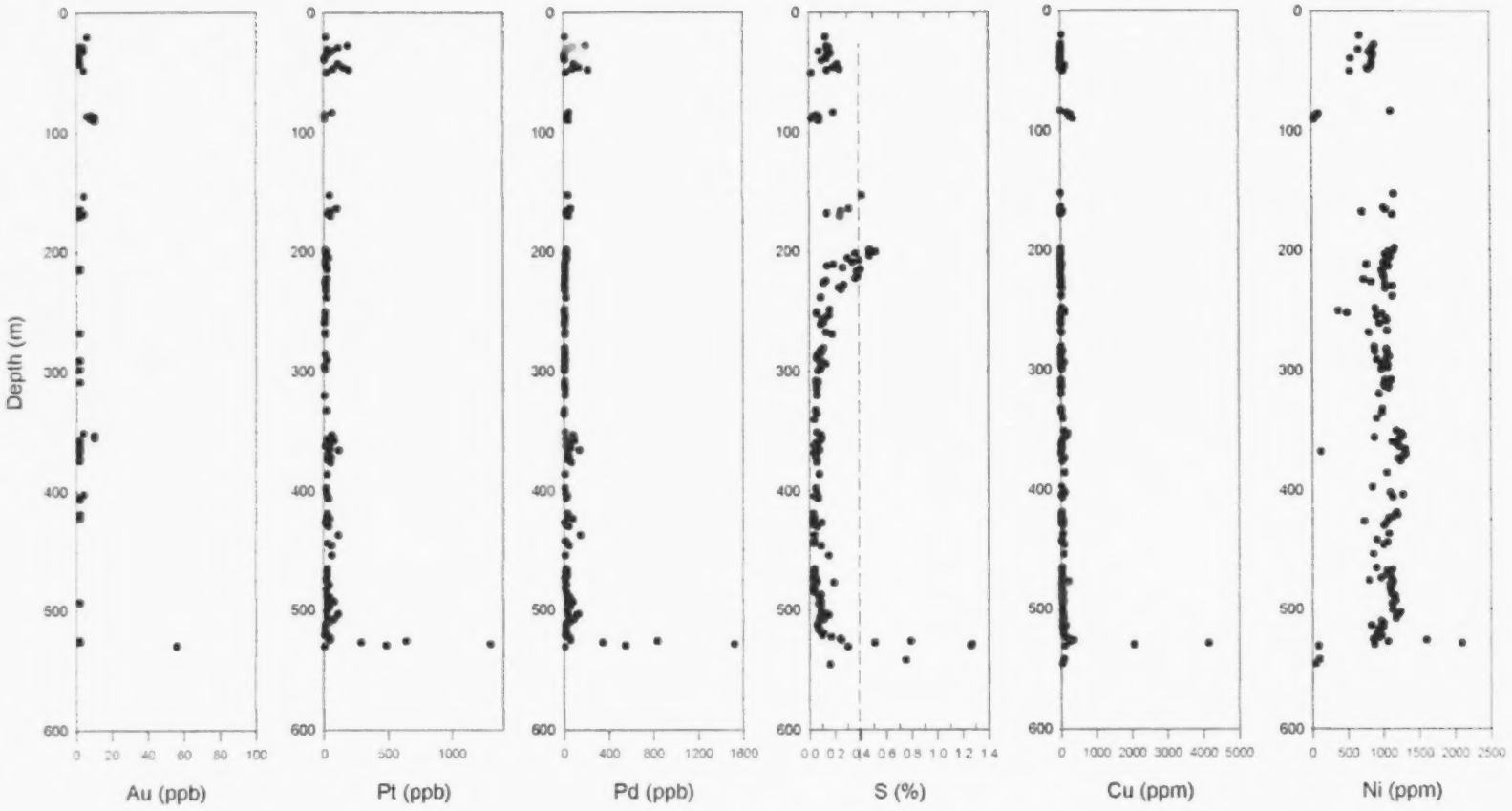

Figure 5. Variation in gold, platinum, palladium, sulphur, copper and nickel content with depth in diamond-drill hole WM00-03. Sulphur saturation at 0.4 weight % (400 ppm) indicated by dashed line.

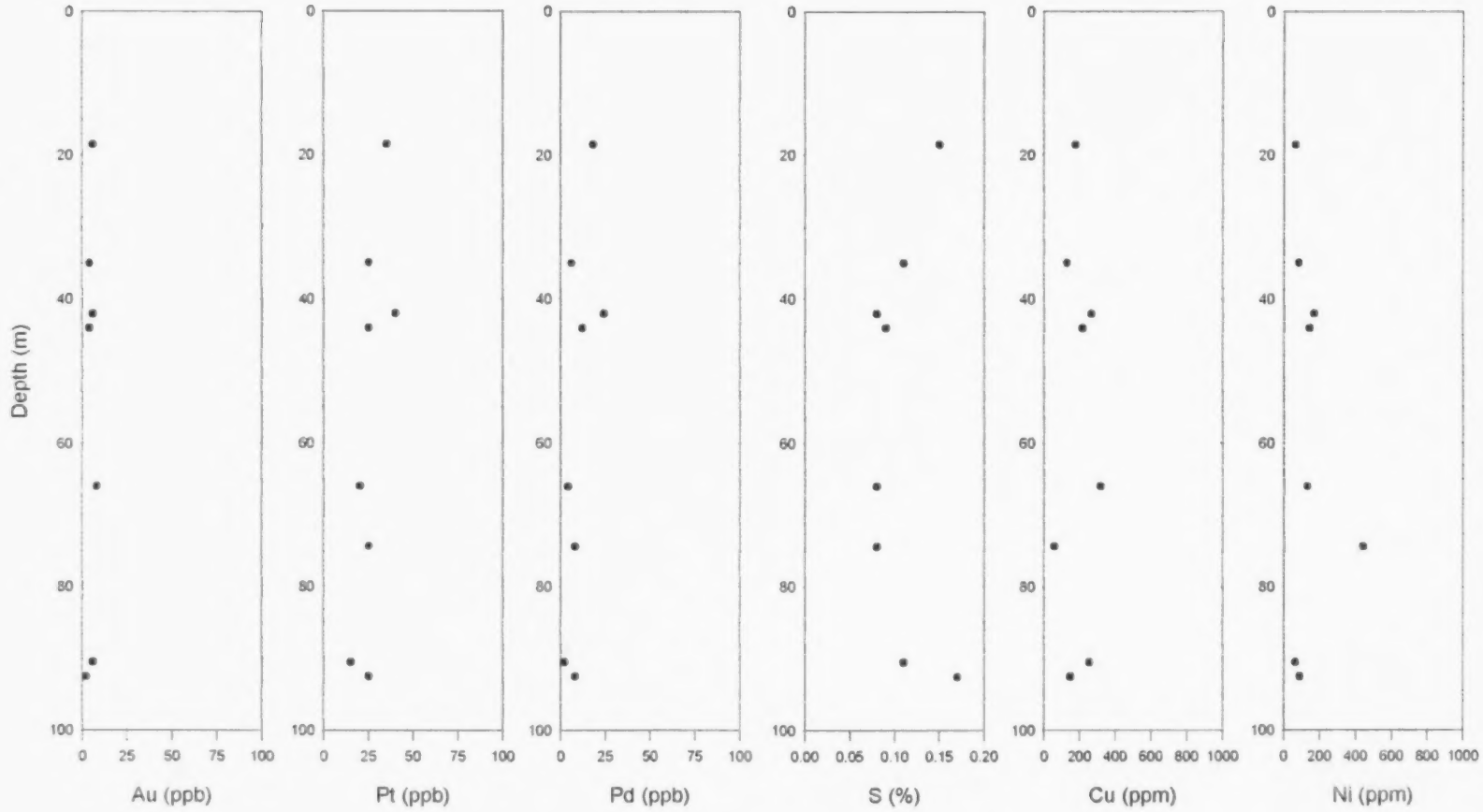

Figure 6. Variation in gold, platinum, palladium, sulphur, copper and nickel content with depth in diamond-drill hole WM00-04. Lack of sulphur saturation correlated with insignificant PGE concentration.

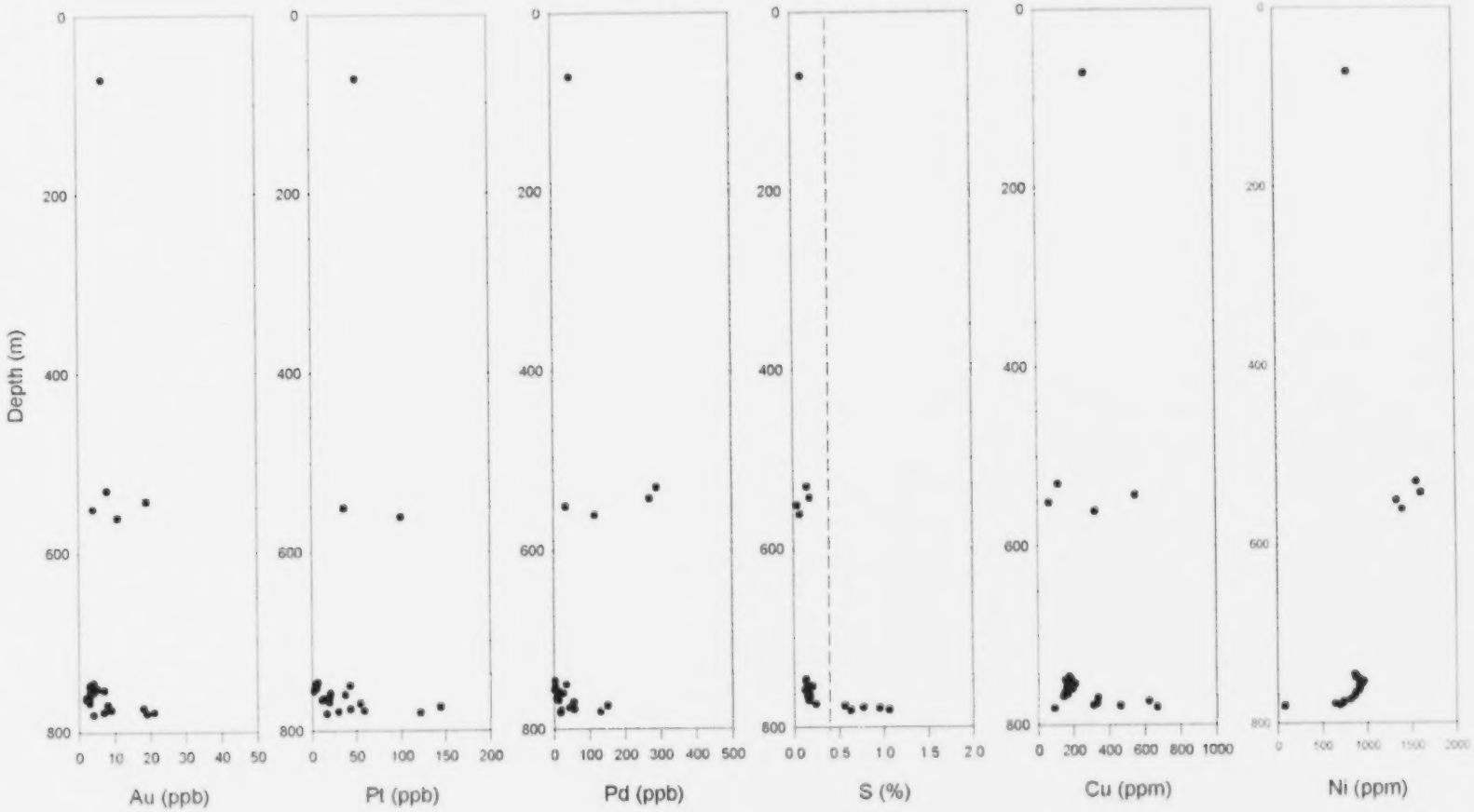

Figure 7. Variation in gold, platinum, palladium, sulphur, copper and nickel content with depth in diamond-drill hole WM00-09. Sulphur saturation at 0.4 weight % (400 ppm) indicated by dashed line.

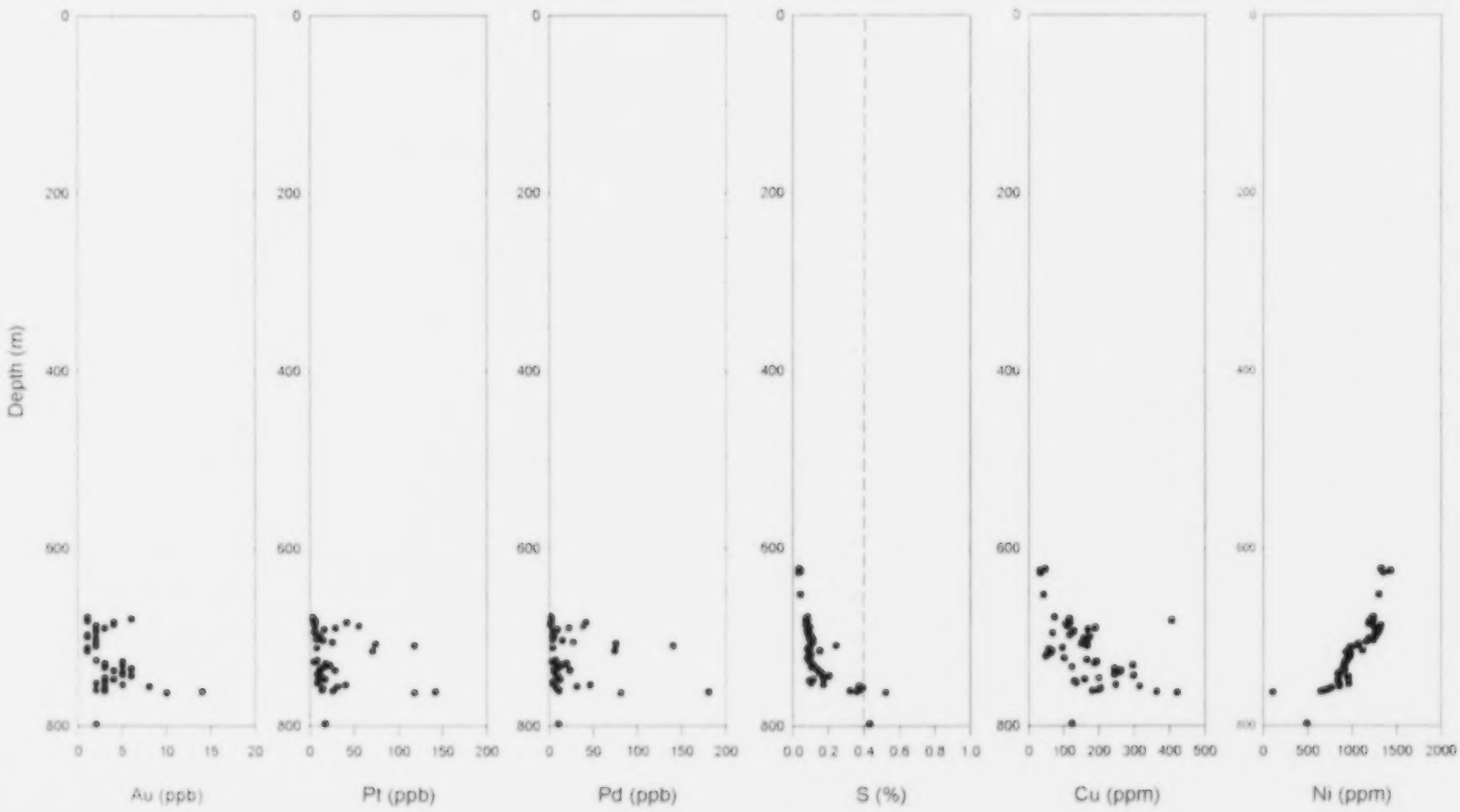

Figure 8. Variation in gold, platinum, palladium, sulphur, copper and nickel content with depth in diamond-drill hole WM00-10. Sulphur saturation at 0.4 weight % (400 ppm) indicated by dashed line.

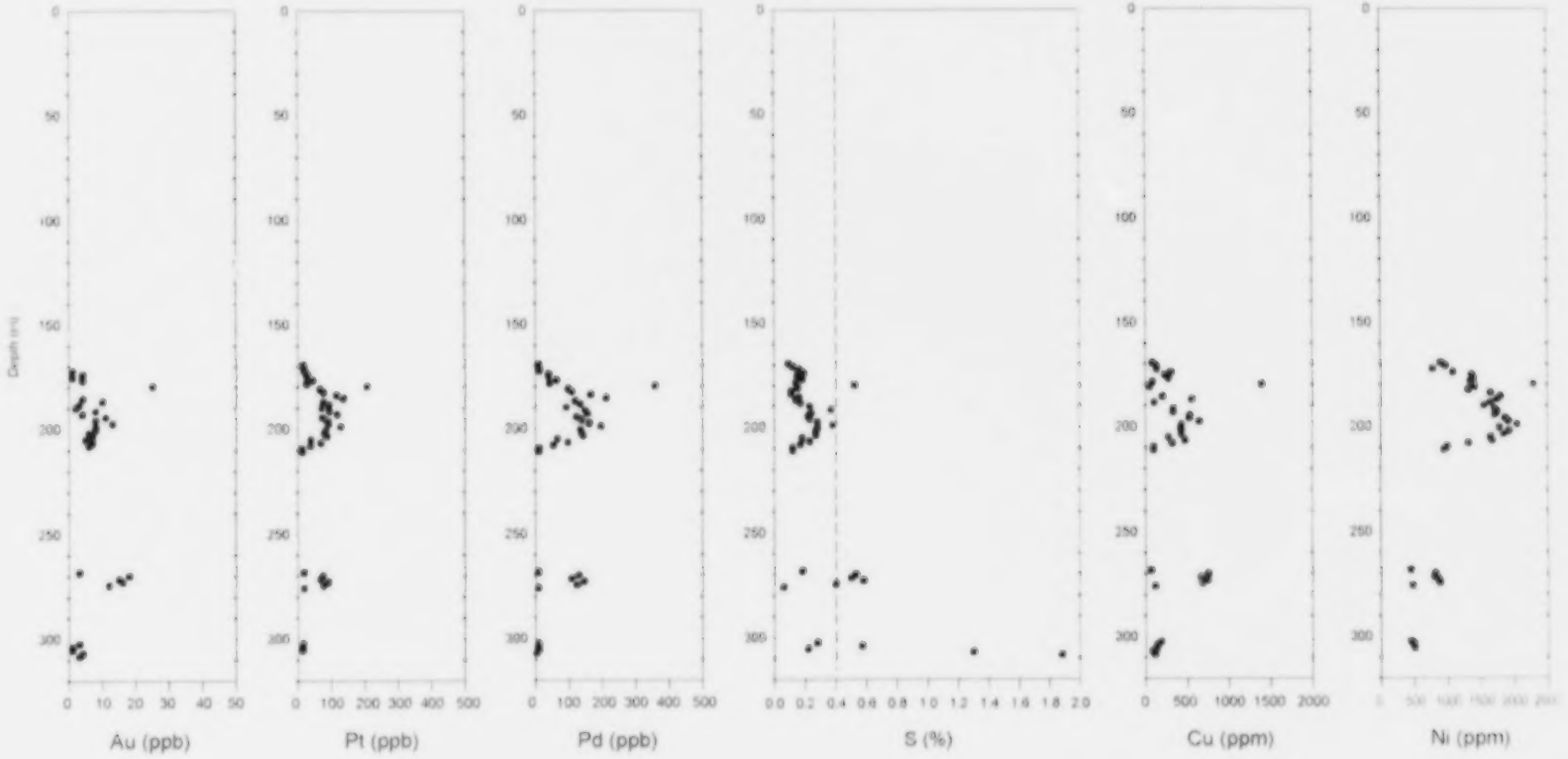

Figure 9. Variation in gold, platinum, palladium, sulphur, copper and nickel content with depth in diamond-drill hole EK02-03. Sulphur saturation at 0.4 weight % (400 ppm) indicated by dashed line.

Metric Conversion Table

Conversion from SI to Imperial			Conversion from Imperial to SI		
SI Unit	*Multiplied by*	*Gives*	*Imperial Unit*	*Multiplied by*	*Gives*
		LENGTH			
1 mm	0.039 37	inches	1 inch	**25.4**	mm
1 cm	0.393 70	inches	1 inch	**2.54**	cm
1 m	3.280 84	feet	1 foot	**0.304 8**	m
1 m	0.049 709	chains	1 chain	20.116 8	m
1 km	0.621 371	miles (statute)	1 mile (statute)	**1.609 344**	km
		AREA			
1 cm^2	0.155 0	square inches	1 square inch	**6.451 6**	cm^2
1 m^2	10.763 9	square feet	1 square foot	**0.092 903 04**	m^2
1 km^2	0.386 10	square miles	1 square mile	2.589 988	km^2
1 ha	2.471 054	acres	1 acre	0.404 685 6	ha
		VOLUME			
1 cm^3	0.061 023	cubic inches	1 cubic inch	**16.387 064**	cm^3
1 m^3	35.314 7	cubic feet	1 cubic foot	0.028 316 85	m^3
1 m^3	1.307 951	cubic yards	1 cubic yard	0.764 554 86	m^3
		CAPACITY			
1 L	1.759 755	pints	1 pint	0.568 261	L
1 L	0.879 877	quarts	1 quart	1.136 522	L
1 L	0.219 969	gallons	1 gallon	**4.546 090**	L
		MASS			
1 g	0.035 273 962	ounces (avdp)	1 ounce (avdp)	28.349 523	g
1 g	0.032 150 747	ounces (troy)	1 ounce (troy)	**31.103 476 8**	g
1 kg	2.204 622 6	pounds (avdp)	1 pound (avdp)	**0.453 592 37**	kg
1 kg	0.001 102 3	tons (short)	1 ton (short)	**907.184 74**	kg
1 t	1.102 311 3	tons (short)	1 ton (short)	**0.907 184 74**	t
1 kg	0.000 984 21	tons (long)	1 ton (long)	**1016.046 908 8**	kg
1 t	0.984 206 5	tons (long)	1 ton (long)	**1.016 046 90**	t
		CONCENTRATION			
1 g/t	0.029 166 6	ounce (troy)/ ton (short)	1 ounce (troy)/ ton (short)	34.285 714 2	g/t
1 g/t	0.583 333 33	pennyweights/ ton (short)	1 pennyweight/ ton (short)	1.714 285 7	g/t

OTHER USEFUL CONVERSION FACTORS

	Multiplied by	
1 ounce (troy) per ton (short)	31.103 477	grams per ton (short)
1 gram per ton (short)	0.032 151	ounces (troy) per ton (short)
1 ounce (troy) per ton (short)	20.0	pennyweights per ton (short)
1 pennyweight per ton (short)	0.05	ounces (troy) per ton (short)

Note: Conversion factors which are in bold type are exact. The conversion factors have been taken from or have been derived from factors given in the Metric Practice Guide for the Canadian Mining and Metallurgical Industries, published by the Mining Association of Canada in co-operation with the Coal Association of Canada.

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